Rapidity fluctuations in the initial state

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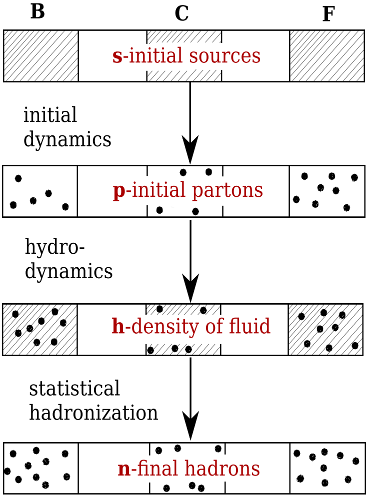
Motivation/new data

- Old story . . .
- New data from the LHC, new methodology (ATLAS notes 2015)
- Longitudinally-extended source model

Goal: understand key elements from an analytic model

anatomy of the correlations

3-stage approach



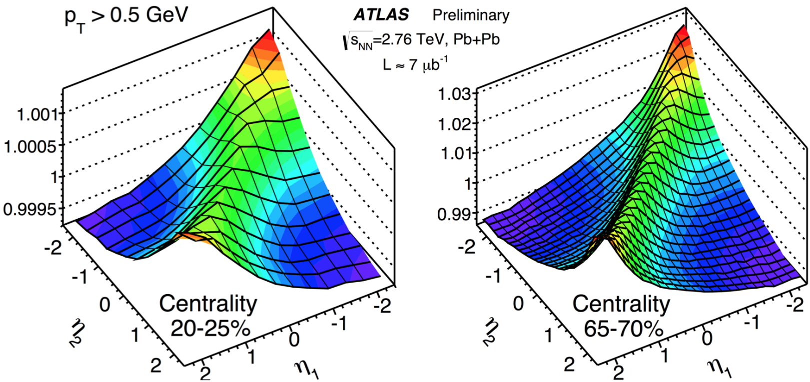
Generation and propagation of e-by-e fluctuations, $\eta_S \to \eta$

New data

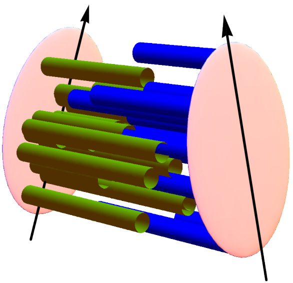
$$C(\eta_1, \eta_2) = \frac{\langle N(\eta_1, \eta_2)\rangle}{\langle N(\eta_1)\rangle\langle N(\eta_2)\rangle} = \frac{S(\eta_1, \eta_2)}{B(\eta_1, \eta_2)}$$

$$C_N(\eta_1, \eta_2) = \frac{C(\eta_1, \eta_2)}{C_p(\eta_1)C_p(\eta_2)}, \quad C_p(\eta_1) = \int d\eta_2 C(\eta_1, \eta_2), \; C_p(\eta_2) = \ldots$$

η_1 and η_2 – pseudorapidities of different hadrons



Rapidity-extended source model



$$
\begin{aligned}
\langle N(\eta_1)N(\eta_2)\rangle &= \langle N_A\rangle\langle f_A(\eta_1,\eta_2)\rangle + \langle N_A(N_A-1)\rangle\langle f_A(\eta_1)\rangle\langle f_A(\eta_2)\rangle \\
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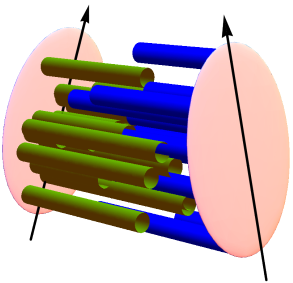

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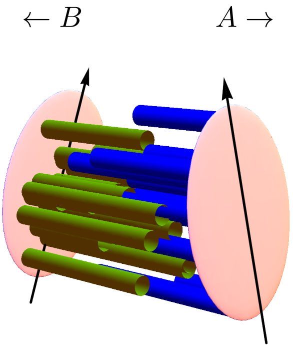

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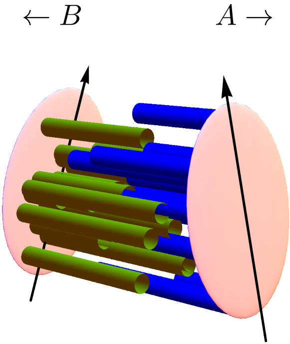

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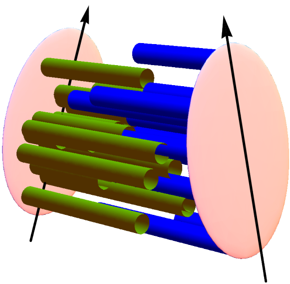


$$\begin{aligned}\langle N(\eta_1)N(\eta_2)\rangle &= \langle N_A\rangle \mathrm{cov}_A(\eta_1,\eta_2) + \langle N_A^2\rangle\langle f_A(\eta_1)\rangle\langle f_A(\eta_2)\rangle \\ &+ \langle N_B\rangle \mathrm{cov}_B(\eta_1,\eta_2) + \langle N_B^2\rangle\langle f_B(\eta_1)\rangle\langle f_B(\eta_2)\rangle \\ &+ \langle N_A N_B\rangle\left[\langle f_A(\eta_1)\rangle\langle f_B(\eta_2)\rangle + \langle f_B(\eta_1)\rangle\langle f_A(\eta_2)\rangle\right]\end{aligned}$$

Production is independent/uncorrelated, unless from the same source.

However, even if $\mathrm{cov}_{A,B}(\eta_1,\eta_2) = 0$ we have nontrivial $C(\eta_1,\eta_2)$ from the fluctuation of numbers of sources N_A and N_B

Rapidity-extended source model

Average number of particles:

$$\langle N(\eta)\rangle = \langle N_A\rangle\langle f_A(\eta)\rangle + \langle N_B\rangle\langle f_B(\eta)\rangle$$

Symmetric and antisymmetric parts (see next slide):

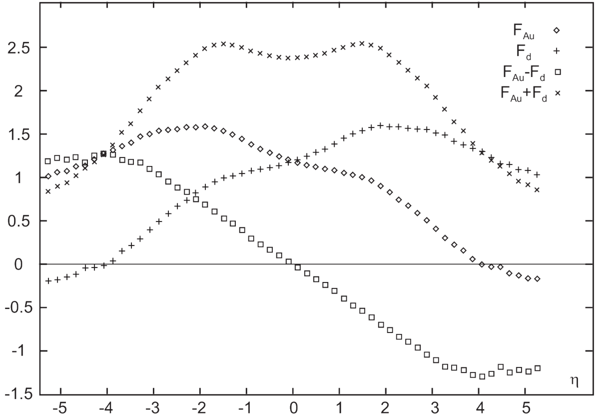
$$\langle f_A(\eta)\rangle = f_s(\eta) + f_a(\eta), \quad \langle f_B(\eta)\rangle = f_s(\eta) - f_a(\eta)$$

After elementary transformations

$$\begin{aligned} C(\eta_1,\eta_2) &= 1 + \frac{1}{\langle N(\eta_1)\rangle\langle N(\eta_2)\rangle} \times \\ & \Big\{ \langle N_A\rangle \mathrm{cov}_A(\eta_1,\eta_2) + \langle N_B\rangle \mathrm{cov}_B(\eta_1,\eta_2) \\ &+ \mathrm{var}(N_A+N_B) f_s(\eta_1) f_s(\eta_2) + \mathrm{var}(N_A-N_B) f_a(\eta_1) f_a(\eta_2) \\ &+ [\mathrm{var}(N_A) - \mathrm{var}(N_B)]\,[f_s(\eta_1) f_a(\eta_2) + f_a(\eta_1) f_s(\eta_2)] \Big\} \end{aligned}$$

Białas-Czyż triangles

Charged hadron spectra in d+Au @ RHIC [Białas+Czyż 2004]



$$\langle f_A(\eta)\rangle = h(\eta)\frac{y_b+\eta}{2y_b}, \;\; \langle f_B(\eta)\rangle = h(\eta)\frac{y_b-\eta}{2y_b}$$

Asymmetric profiles used ever since . . .

Observation by Bzdak and Teaney

Vanishing covariance, symmetric system, profiles from the previous slide:

$$\langle N_A \rangle = \langle N_B \rangle, \quad \mathrm{var}(N_A) = \mathrm{var}(N_B), \quad N_W = N_A + N_B$$

Then

$$C(\eta_1, \eta_2) = 1 + \frac{1}{\langle N_W \rangle^2} \left[\mathrm{var}(N_W) + \mathrm{var}(N_A - N_B) \frac{\eta_1}{y_b} \frac{\eta_2}{y_b} \right]$$

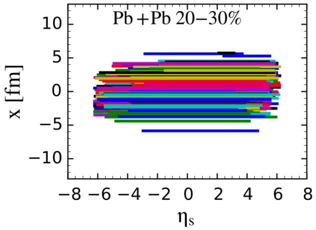
[Bzdak+Teaney 2013]

Fluctuations of N_A vs N_B cause the $\eta_1 \eta_2$ structure in $C(\eta_1, \eta_2)$

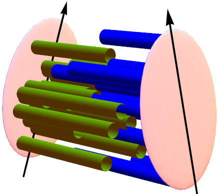
Fluctuating length

- Idea: entropy deposition from wounded nucleons originates from string-like objects whose other end-point is randomly distributed in η (related to [Brodsky+Gunion+Kuhn 1977])
- String fragmentation
- *"Soft particle production in hadronic collisions is dominated by multiple gluon exchanges between partons from the colliding hadrons, followed by radiation of ... partons distributed uniformly in rapidity"* [Białas+Jeżabek 2004]
- Torque in p-A collisions (see talk by PB) [PB+WB, arXiv:1506.02817]
- Similar ideas in [Monnai+Schenke, arXiv:1509.04103]
- Built-in into existing models/codes

e.g., HIJING [L.-G. Pang, QM2015]:



What it yields?



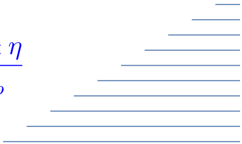
$$f_A(\eta;y)=\theta(y<\eta<y_b),\quad f_B(\eta;y)=\theta(-y_b<\eta<-y)$$

(uniform string fragmentation function)

Random end y is uniformly selected from $[-y_b, y_b]$, where y_b is the beam rapidity

Averaging over $y \to$ "triangles":

$$\langle f_{A,B}(\eta)\rangle = \int_{-y_b}^{y_b} \frac{dy}{2y_b} f_{A,B}(\eta;y) = \frac{y_b \pm \eta}{2y_b}$$



Correlations from length fluctuations:

$$\langle f_{A,B}(\eta_1,\eta_2)\rangle = \int_{-y_b}^{y_b} dy f_{A,B}(\eta_1;y) f_{A,B}(\eta_2;y) = \frac{y_b \pm \min(\eta_1,\eta_2)}{2y_b}$$

$$\mathrm{cov}_{A,B}(\eta_1,\eta_2) = \frac{y_b^2 - \eta_1\eta_2 - y_b|\eta_1-\eta_2|}{4y_b^2}$$

Fluctuating strength

An additional ingredient:

$$f_A(\eta; y) = \omega\theta(y < \eta < y_b), \quad f_B(\eta; y) = \omega\theta(-y_b < \eta < -y)$$

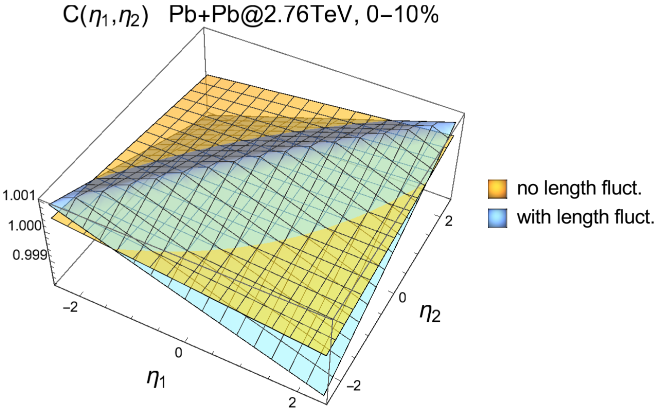
ω – random strength of the source
(included in models to increase multiplicity fluctuations)

Also known as overlaid distribution

(we use $\sigma(\omega)/\langle\omega\rangle = 1$ on top of fluctuating length)

Results for C

$$C(\eta_1,\eta_2) \to \frac{C(\eta_1,\eta_2)}{\int_{-Y}^{Y}\frac{d\eta_1}{2Y}\int_{-Y}^{Y}\frac{d\eta_2}{2Y}C(\eta_1,\eta_2)} \quad \text{(normalization to 1)}$$



Generation of the ridge (structure from $-|\eta_1-\eta_2|$)

Fluctuating length essential

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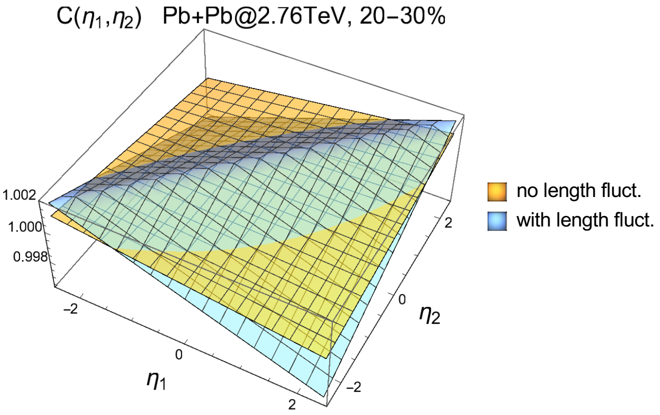

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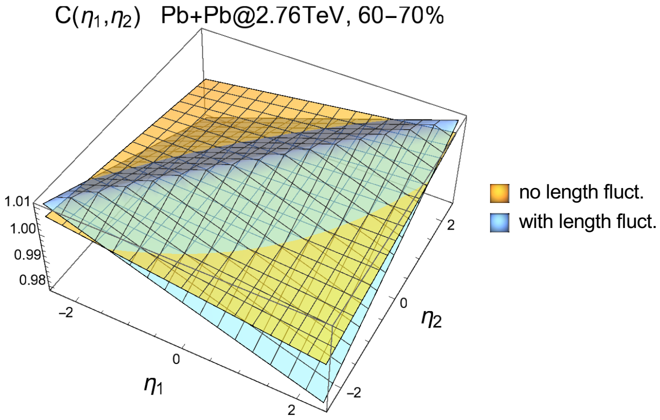

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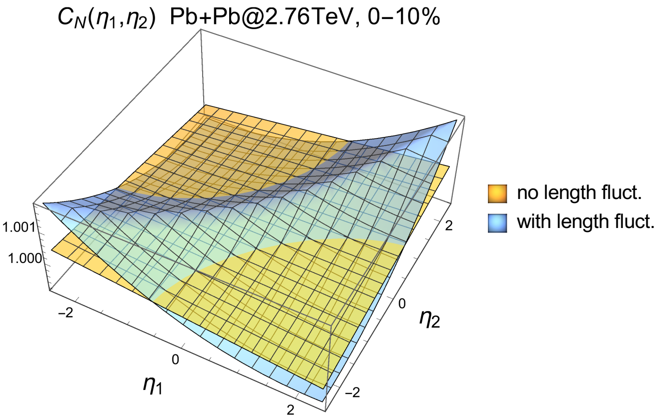

Generation of the saddle in the ridge (seen in experiment) is trivial

Fluctuating length essential

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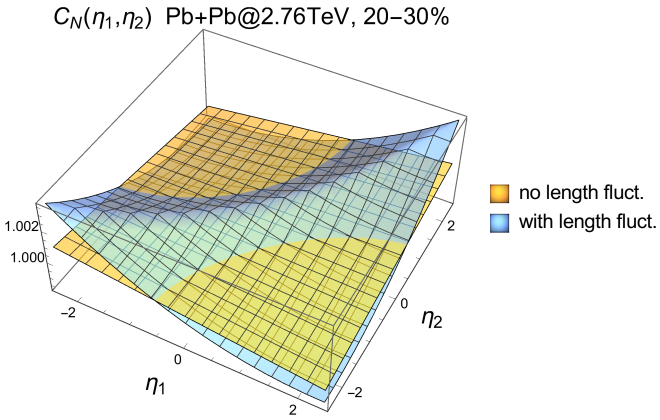

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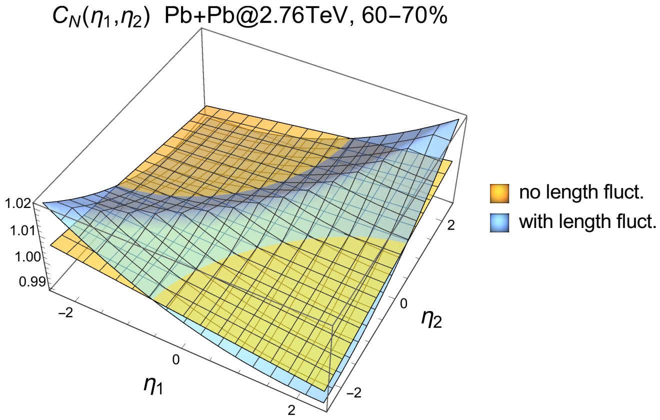

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a_{nm} coefficients

$$a_{nm} = \int_{-Y}^{Y} \frac{d\eta_1}{Y} \int_{-Y}^{Y} \frac{d\eta_2}{Y} C(\eta_1, \eta_2) T_n\left(\frac{\eta_1}{Y}\right) T_m\left(\frac{\eta_1}{Y}\right)$$

$$T_n(x) = \sqrt{\frac{2n+1}{2}} P_n(x)$$

[Bzdak+Teaney 2013, Jia 2015]

(play analogous role to flow coefficients in harmonic flow)

$$a_{nn} = \frac{\frac{\mathrm{var}(N_A - N_B)}{\langle N_W \rangle} + \frac{\mathrm{var}(\omega)}{\langle \omega \rangle^2}}{12\langle N_W \rangle} \frac{Y^2}{y_p^2} \delta_{n1} - \frac{\frac{\mathrm{var}(\omega)}{\langle \omega \rangle^2} + 1}{6\langle N_W \rangle} \frac{Y^2}{y_p^2} \delta_{n1} + \frac{\frac{\mathrm{var}(\omega)}{\langle \omega \rangle^2} + 1}{(2n-1)(2n+3)\langle N_W \rangle} \frac{Y}{y_p}$$

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– qualitatively as in experiment

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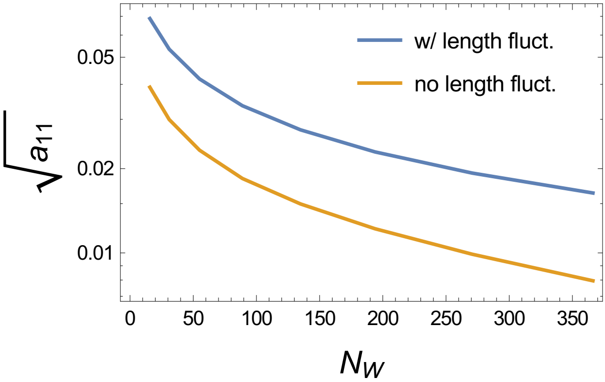

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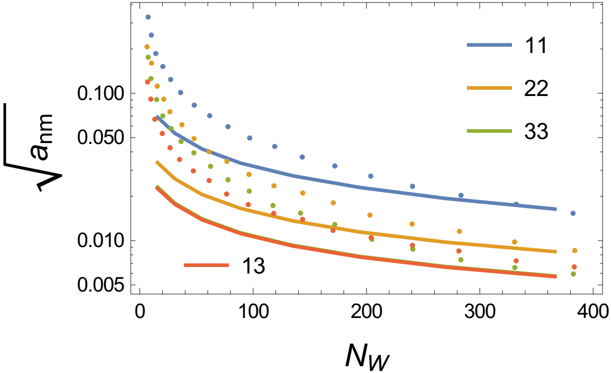

Exp. $\sim N_w^{-0.7}$, model: $\sim N_w^{-0.5}$ (newest ATLAS analysis shows $\sim N_{ch}^{-0.5}$, N_{ch} – number of observed charged hadrons)

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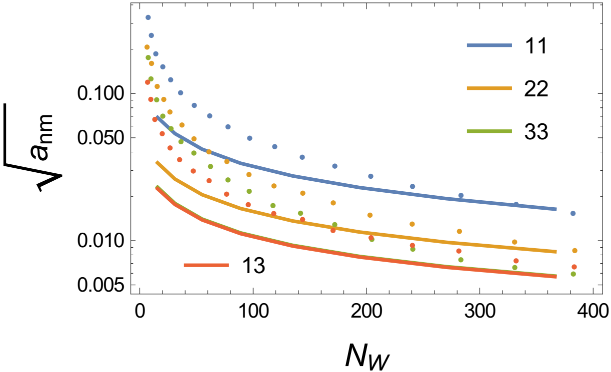

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Need linear response from N_{sources} to N_{ch}!

From initial state to final hadrons

- $\eta_S \to \eta$, some extra hydro push $\to$ reduction of a_{nm}
- resonance decays – relevant effect [PB+WB+A. Olszewski 2015] $\to$ increase
- charge conservation, other correlations – not included
- removal of the short-range effects (discussed in a while)

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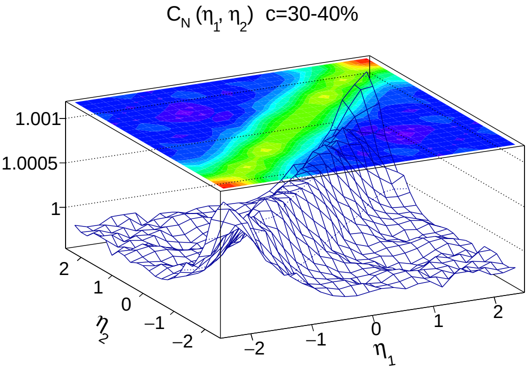
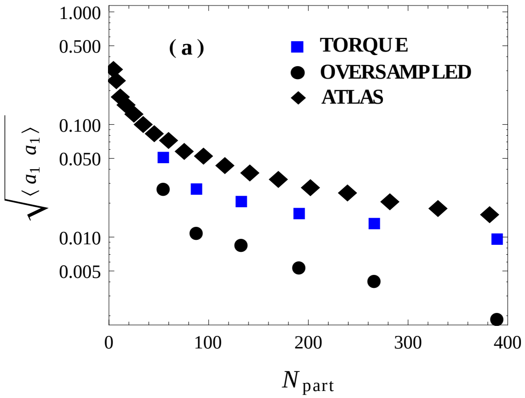
Hydro (no length fluctuations included here):



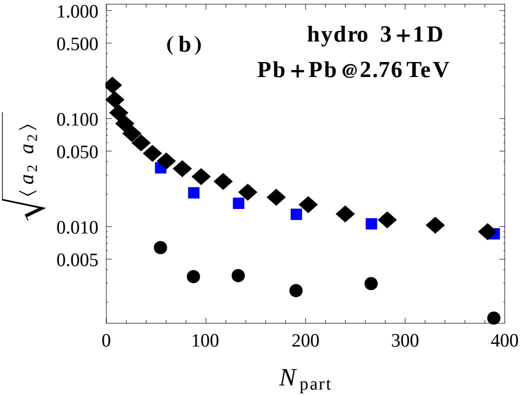
a_{nm} from hydro



$\langle a_n a_m \rangle = a_{nm}$, "torque"=our model without length fluct., "oversampled"=no resonance decays

About 50% of $\sqrt{a_{11}}$ from resonances!

a_{nm} from hydro



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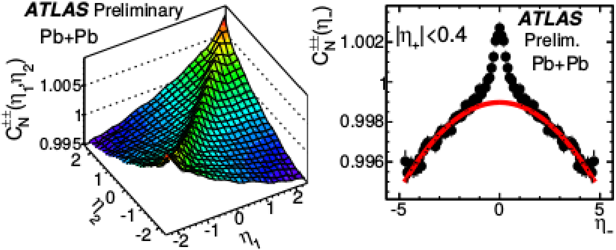
Removing the short-range defects

Rather involved experimental procedure, which gets rid of correlations shorter that ~ 1 unit in $\eta_1 - \eta_2$



Removes resonances, jets, ..., some of the source fluctuations

After the procedure only a_{11} survives in exp., other =0 (do not throw out the baby with the bath water!)

It should be carried out in a model simulation

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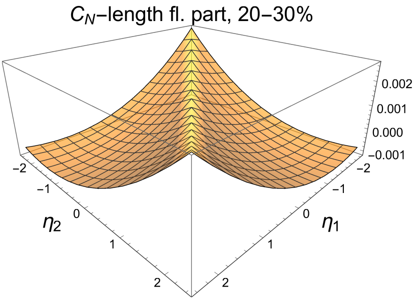

Removes resonances, jets, ..., some of the source fluctuations
After the procedure only a_{11} survives in exp., other =0 (do not throw out the baby with the bath water!)

It should be carried out in a model simulation

Conclusions

- Data: need for extra longitudinal fluctuations in the initial state (see also the talk by Piotr Bożek, torque in p+Pb)
- No collectivity, no flow needed – robust analysis
- Anatomy:
  - Early stage: N_A vs N_B fluctuations, strength fluctuations, length fluctuations
  - Late stage: resonance decays (large effect), conservation laws
- Many sources required, $1/N$ effect
- $1/\sqrt{N_{ch}}$ scaling of $\sqrt{a_{11}}$ $\to$ linear relation between $N_{\rm sources}$ and N_{ch}
- Intricate procedures: $C \to C_N$, normalization, removing short-range correlations – necessary in modeling for 1-1 comparisons